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16. ABSTRACT The paper is an overview of flare research conducted by EPA and the Energy and Environmental Research Corporation (EER) in 1984. Initial work by EER for EPA focussed on developing a basic understanding of the flaring process, reviewing data on flare combustion efficiency, and designing a facility for evaluating flare emissions. A Flare Test Facility was constructed, and tests were conducted. The tests provided data showing a minimum heating value required to achieve flame stability at a given velocity. The results also showed that unstable flames tend to produce low combustion efficiencies. Other studies have also explored the use of flares as control devices for VOCs. VOC combustion of 90% (or greater) have been reported for pilot scale flares within specific ranges of gas heating value and gas exit velocity. The research reported in this paper was designed to determine: (1) the effect of flare head design on flame stability and combustion efficiency, and (2) the destruction efficiency of specific compounds in relation to flare operating parameters.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Organic Compounds	Stationary Sources	07C
Volatility	Flaring	20M
Combustion Efficiency	Volatile Organic Compounds	21B
Gases		07D
Gas Analysis		14B

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FLARE EFFICIENCY - THE INFLUENCE OF FLARE HEAD DESIGN AND GAS COMPOSITION

Introduction

The effect of flare operations on the environment continues to be of concern to regulatory agencies and industry. Assessing flare emissions of unburned volatile organic compounds (VOC's) requires a determination of overall combustion efficiency. In addition, concern over the emission of potentially toxic air pollutants from flares requires that the destruction efficiency for specific compounds be determined. In order to obtain such information, the U.S. Environmental Protection Agency is sponsoring a flare research program under a contract to Energy and Environmental Research Corporation (EER). This paper provides an overview of the flare research conducted by EPA/EER in 1984.

Background

Initial work under EPA Contract 68-02-3661 by EER focussed on developing a basic understanding of the flaring process, reviewing data on flare combustion efficiency, and designing a facility for evaluating flare emissions[1]. A Flare Test Facility was constructed, and tests were conducted on simple pipe flares, with and without steam injection, ranging from 3 to 12 in.* in diameter. Three 12-in. steam assisted flares provided by manufacturers were also tested. Gas exit velocities and heating values were varied over a wide range using propane/nitrogen mixtures. These tests produced data showing a minimum heating value required to achieve flame stability at a given velocity[2].

The term "flame stability" means that a flame is maintained; flame instability occurs when the gas exit velocity exceeds the flame velocity and the flame goes out. Figure 1 shows the gas exit velocity at the point of instability (i.e., at the point where the flame starts to go out). This point was determined by establishing a propane/nitrogen flame at a given velocity and then decreasing the flow of propane until the flame went out. The propane flow was then increased slightly, the flare was relit, and combustion efficiency measurements were conducted. The shaded area shown in Figure 1 indicates the minimum gas heating value required to produce a stable flame at the gas exit velocity within the 95 percent confidence interval of the mean. For any given velocity, a gas with a heating value above this region produces a stable flame; a gas with a heating value below the region produces an unstable flame. Thus, for any given exit velocity, the minimum gas heating value required for a stable flame can be determined.

The results also showed that unstable flames tend to produce low combustion efficiencies. Figure 2 plots combustion efficiency vs. the ratio of gas heating value to the minimum heating value required for a stable flame. This shows that when the ratio exceeds 1 (i.e., a stable flame), high combustion

*See CONVERSION FACTORS at end of paper for metric equivalents for all units used in this paper.

efficiencies are achieved. When the ratio is less than 1 (unstable flame), lower combustion efficiencies are often obtained.

Other studies have also explored the use of flares as control devices for VOC's[3-8]. Both Siegel[6] and McDaniel [8] reported 98 percent (or greater) VOC combustion for pilot scale flares within specific ranges of gas heating value and gas exit velocity.

While past studies and the recent EPA/EER work have provided extensive data on flare performance, questions remain and additional research is needed. The research reported in this paper is an extension of the earlier EPA/EER work, and it was designed to meet two objectives:

1) Determine the effect of flare head design on flame stability and combustion efficiency.

This objective was developed to extend the data base beyond pipe and steam-assisted flares to include other commonly used flare head designs, such as pressure flare heads, Coanda steam injection flares, and air assisted flares.

2) Determine the destruction efficiency of specific compounds in relation to flare operating parameters.

Previous studies focussed on VOC combustion efficiency, and no information on compound specific destruction was obtained. This objective was designed to fill that gap. Flares often burn mixtures of organic compounds or inorganic compounds with or without a carrier gas. In such cases, the destruction efficiency of individual compounds may not correspond to the overall flare combustion efficiency.

Discussion

EPA/EER Flare Test Facility

A large Flare Test Facility (FTF) was designed and built by Energy and Environmental Research Corporation (EER) under sponsorship of the U.S. Environmental Protection Agency (EPA). The FTF has been previously described[2]. The purpose of this facility is to measure the performance of pilot-scale and commercial flare heads up to 12 in. in diameter. Similar testing of flare heads in commercial operation would be impossible due to problems in measurement, and the uncertainty caused by natural variations in conditions of flow and composition of the gases flares as well as safety concerns.

The FTF depicted in Figure 3 consists of support scaffolding, a test flare head, a gas delivery system, and a sampling system. The scaffolding is 20 x 30 x 60 ft high, and supports an 8 ft high wind screen with 22.7 percent open area. The gas system is capable of delivering 28,000 ft^3/hr. The flow rate of the gases is measured over a wide range of flow by use of calibrated parallel orifices. Five samples are individually and simultaneously withdrawn for soot, CO, HC, CO_2, O_2, SO_2, H_2S, NH_3, NO, and NO_2 through a moveable, steam-heated five-position rake probe. Samples can also be captured on Tenax®-charcoal

traps for gas chromatograph-mass spectrometer analysis. Samples are drawn and mixed for 20 minutes to average flame fluctuations.

The local and global combustion and destruction efficiencies are obtained through mass balances, use of a tracer to determine the dilution factor, and integration across the flare plume. The local dilution factors are determined from the measured and background composition and the known theoretical composition for complete destruction of the gas flared at a stoichiometric ratio of 1. Local combustion and destruction efficiencies are determined from the composition corrected to the stoichiometric ratio of 1. Global combustion and destruction efficiencies are obtained by integrating the sample results across the flare flame plume. This is accomplished by using the compositions measured at different positions and a velocity estimated at each position using jet theory.

Flare Head Design

In 1984, the following flare heads were evaluated: a) two pressure flares (1-1/2 in. nominal diameter); b) one Coanda steam injection flare (12 in. nominal diameter); and c) one air assisted flare (1-1/2 in. nominal diameter). All flares were designed and built by commercial vendors.

As discussed, previous studies at the FTF showed that combustion efficiency was related to the stability of the flare flame as defined by the relationship between the exit velocity and the gas heating value (see Figures 1 and 2). This same procedure was used to analyze the data collected for the different flare head designs.

Figures 4 and 5 show these relationships for the two pressure heads. Note that head "F" has an open area almost twice as large as head "E." Combustion efficiencies were generally greater than 98 percent for heating values more than 10 percent above that required for a stable flame. Both heads provided a stable flame at heating values lower than those required for pipe flares, although differences between the stability limits for the two pressure heads were substantial.

The data for the Coanda steam injection head are provided in Figure 6. These results are consistent with previous results, including the work of Siegel[6] on Coanda flares.

The data on flame stability for the air assisted flare are shown in Figure 7 for tests conducted both with and without a pilot flame. These data do not show a relationship between exit velocity and gas heating value for flame stability which is consistent with other flare heads. (The gas exit velocity does not incude the air provided by the fan.) The ratio (by weight) of air to propane are shown beside each data point in Figure 7. Since a stability relationship could not be developed, the relationship between heating value and combustion efficiency is also unclear. Further analyses and data are needed to clarify the situation. Table 1 provides data on combustion efficiencies measured on the air assisted flare. These data show that low combustion efficiencies are associated with high air-to-fuel ratios, which is consistent with previous work on air assisted flares[8].

Compound Destruction Efficiency

Previous tests of combustion efficiency at the FTF were conducted on mixtures of propane and nitrogen. Since a wide variety of compounds are flared in practice, data on the destruction efficiency of individual compounds are needed. A small, laboratory scale burner (1/16-in. OD tube) was used to inexpensively evaluate the effect of compound type on destruction efficiency. Table 2 shows these results for 21 compounds. It is emphasized that these tests do not simulate flare flames due to the small nozzle diameter. They were conducted to allow a large number of compounds to be "screened" without resorting to the high cost of FTF testing. These screening tests allowed qualitative evaluations of the following factors: a) ignition problems, b) potentially low destruction efficiencies, and c) soot production. As highlighted in Table 2, several compounds exhibited these potential problems. Three of these compounds (1,3-butadiene, ethylene oxide, and ammonia) and hydrogen sulfide were subsequently selected for testing on the FTF. Budget limitations prevented FTF tests on a larger number of compounds.

The tests were conducted on a 3-in. pipe flare, and data were collected to determine flame stability, combustion efficiency, and compound destruction efficiency. The relationships for flame stability and combustion efficiency were consistent with previous results, as shown in Figure 8. Note the high combustion efficiencies achieved for all of the mixtures. On the other hand, the relationship between compound destruction efficiency and stability was found to be affected by the compound. Figure 9 shows this effect. Note especially the lower destruction efficiencies for ammonia. The destruction efficiency data for hydrogen sulfide are not provided due to uncertainties concerning the analysis of H_2S. The results show that high VOC combustion efficiencies may not ensure equally high destruction efficiencies for specific compounds. Further tests are being conducted for hydrogen sulfide.

Plans for Future Research

The results of the recent EPA/EER work provide a substantial increase in the information base on flare performance. The results also point to needed research in several areas. The following research needs have been identified and are presented in priority order:

1) Conduct additional tests to determine destruction efficiency values for hydrogen sulfide.

2) Evaluate the effect of pilot flames on flare flame stability and combustion/destruction efficiency.

3) Determine the destruction efficiency of additional compounds.

4) Develop methods (theoretical/empirical) to predict destruction efficiencies for specific compounds and compound classes based on chemical properties, relief gas characteristics, and flare operation.

5) Conduct additional testing on air-assisted flares to develop a clearer relationship between operating parameters and combustion/destruction efficiency.

EPA has allocated funds for fiscal year 1985 which will allow work to proceed on meeting the first three objectives.

Conclusions

The results presented in this paper provide several conclusions relating to flare head design and gas composition.

Flare Head Design

- Pressure flare heads can have different stability curves (heating value vs. exit velocity) when compared to pipe/steam assisted flares.
- Combustion efficiencies for pressure heads and Coanda steam injection heads can be related to the minimum heating value required for a stable flame at a given exit velocity.
- Flame stability for air assisted flares cannot be described by the same relationship between exit velocity and heating value as obtained for other flare head designs.
- Air assisted flares exhibit low combustion efficiencies at high air-to-fuel ratios.

Gas Composition

- Most compounds tested in the small, laboratory screening facility had high destruction efficiencies.
- High VOC combustion efficiency may not ensure equally high destruction efficiency for specific compounds.

Acknowledgements

Data presented in this paper were collected by Energy and Environmental Research Corporation under a program sponsored by the U.S. Environmental Protection Agency (Contract 68-02-3661). The compound screening study was conducted by Elisabeth Poncelet, now in Thonon-Les-Bains, France. The tests at the FTF were conducted by Nicholas Soelberg, with the assistance of Dennis Redican. The guidance and assistance of Bruce Davis, Exxon Chemical Company, in preparing this paper is also acknowledged.

CONVERSION FACTORS

English to Metric Unit Conversion Factors

English Unit	Multiplied by	Conversion Factor	Yields	Metric Unit
Btu		1.055		kJ
ft		0.305		m
ft^3		0.0283		m^3
in.		0.0254		m
lb		0.454		kg

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TABLE 1. TEST RESULTS - AIR ASSISTED FLARE

Exit Velocity ft/sec	Gas Heating Value Btu/ft^3	Air/Propane Ratio	Combustion Efficiency %
98.4	712	15.4	88.8
8.5	547	230	32.1
428	1528	1.6	99.7
69.1	1032	30.4	62.3
425	1425	3.7	99.7
10.9	2350	85	54.5

Note: Tests were conducted with propane/nitrogen mixtures; no pilot flame. Exit velocity based on open area, not including air flow.

TABLE 2. RESULTS OF COMPOUND SCREENING TESTS (GASES IN PROPANE/NITROGEN MIXTURES)

Compound	% Compound in Gas	% Hydrogen in Gas	Heating Value Btu/ft^3	DE[a] %	CE[b] %	Soot (mg/m^3)
Acetylene	100	0	1475	99.99	99.97	<1.5
Ethylene	100	0	1580	99.91	99.92	<1.5
Propylene	100	0	2300	99.98	99.93	<1.5
1,3-Butadiene	100	0	2780	99.93	99.93	75[c]
Butane	100	0	3321	99.99	99.96	<1.5
Propane	100	0	2350	99.98	98.18	<1.5
Propane	25	75	1763	99.97	NA[d]	NA
Benzene	1.50	43	2370	99.59	99.95	<1.0
Toluene	1.50	43	2381	99.99	99.90	<1.0
Chlorobenzene	1.15	43	2350	99.49	99.95	<1.0
Carbon Monoxide	100	0	Could Not Ignite			
Carbon Monoxide	30	44	1760	99.60	99.88	<1.0
Carbon Monoxide	NA	NA	1111	NA	99.42	<1.0
Acetone	1.43	43	2347	99.80	99.96	<1.0
Acetaldehyde	2.07	43	2331	99.99	99.97	<1.5
Ethylene Oxide	1.42	43	2337	96.92	99.95	<1.0
Carbon Dioxide	7.58	43	2171	NA	99.93	<1.0
Methyl Chloride	9.17	42	2212	99.94	99.96	<1.0
Ethylene Dichloride	1.43	43	2335	99.70	99.95	<1.0
Vinyl Chloride	0.11	44	2350	96.79	NA	<1.0
Methyl Mercaptan	10.7	40	2218	99.39	99.82	<1.0
Acrylonitrile	1.47	43	2350	99.99	99.96	<1.0
Hydrogen Cyanide	0.013	44	2350	85.00	NA	<1.0
Ammonia	20	37	1967	99.90	NA	<1.0
Ammonia	100	0	Could Not Ignite			

[a]DE = Destruction Efficiency
[b]CE = Combustion Efficiency
[c]Boxes indicate compounds with potential problems
[d]NA = Not Available

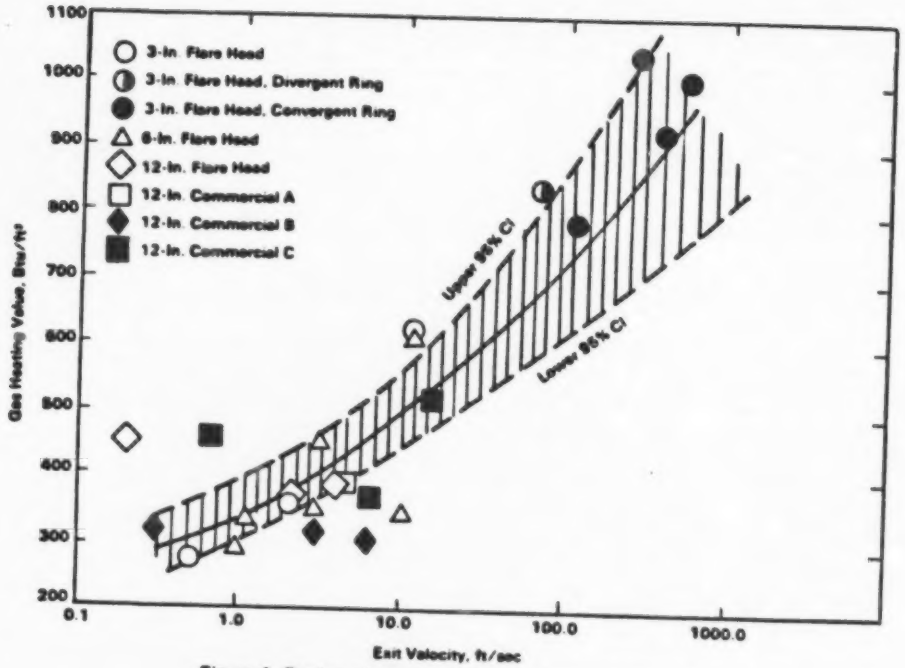


Figure 1. Region of flame instability. (propane/nitrogen)

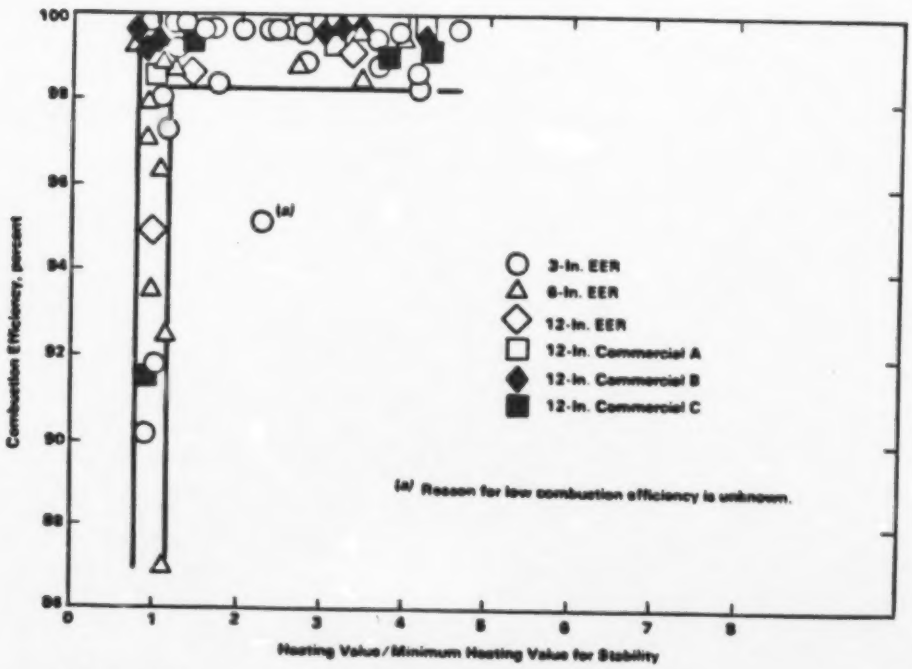


Figure 2. Combustion efficiency vs. flame stability. (propane/nitrogen)

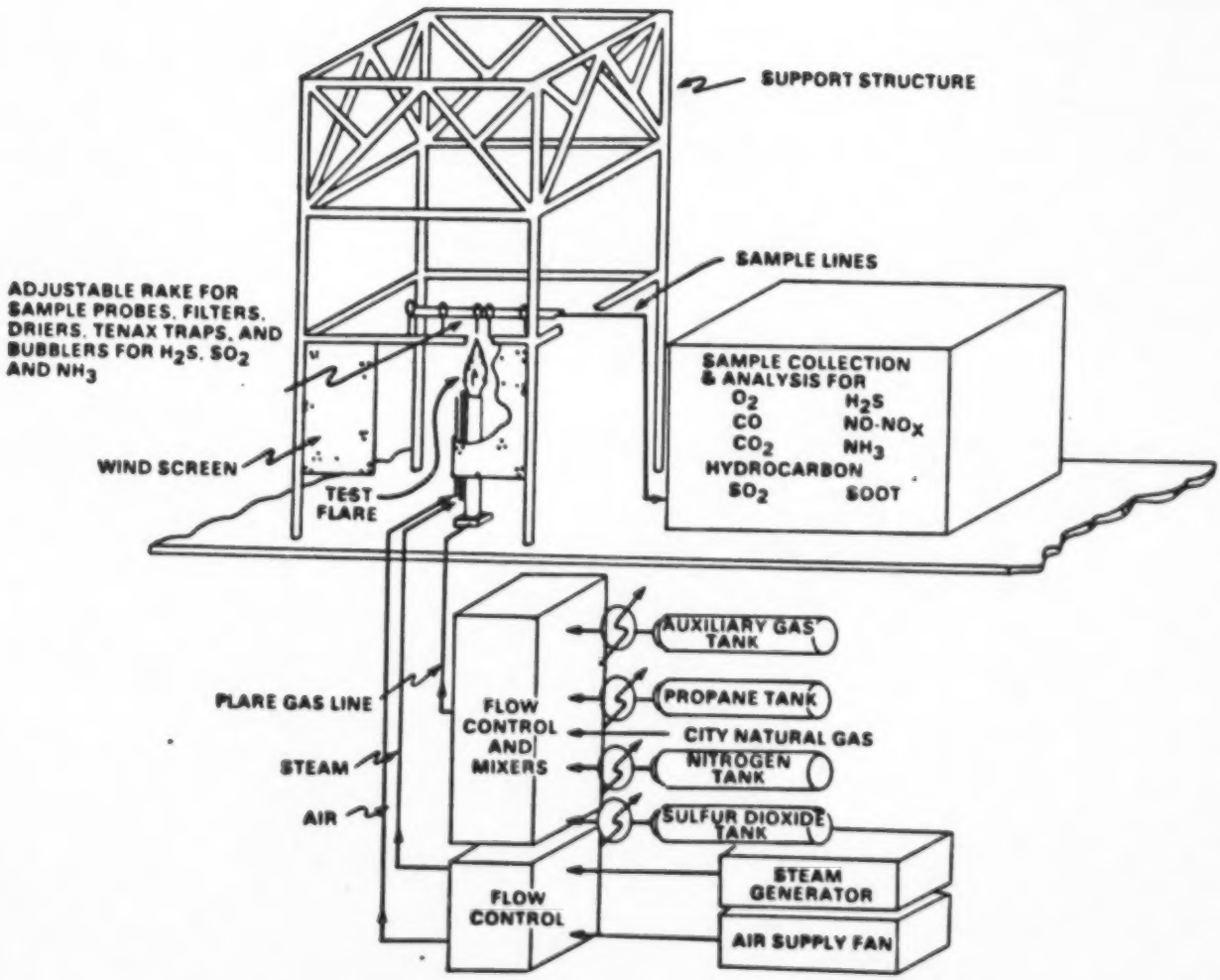
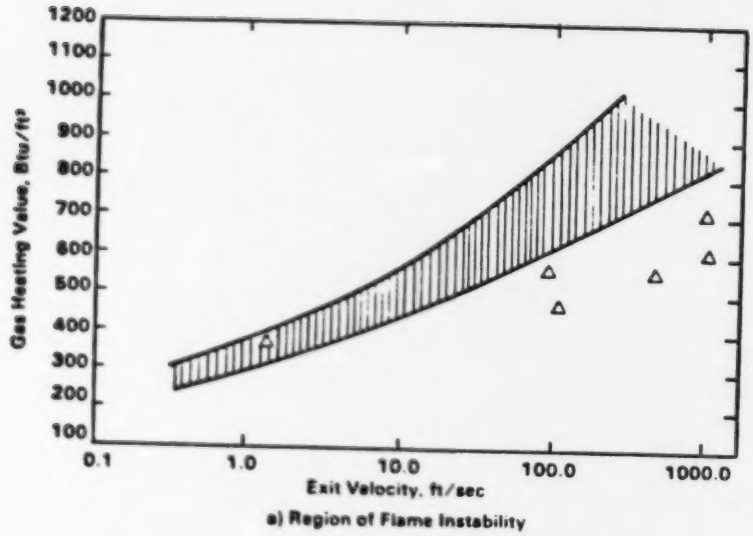
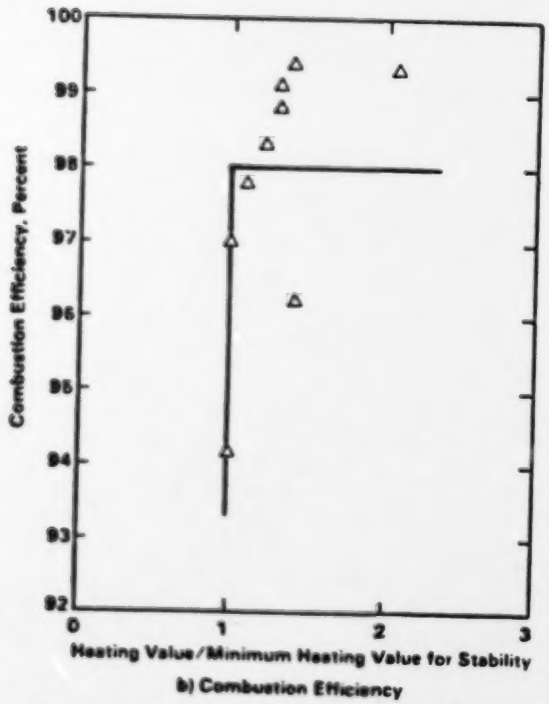


Figure 3. EPA flare test facility (FTF) at Energy and Environmental Research Corporation (EER), El Toro, California.



a) Region of Flame Instability



b) Combustion Efficiency

Figure 4. Region of flame stability and combustion efficiency for a commercial 1-½-in. pressure flare head E burning propane/nitrogen mixtures.

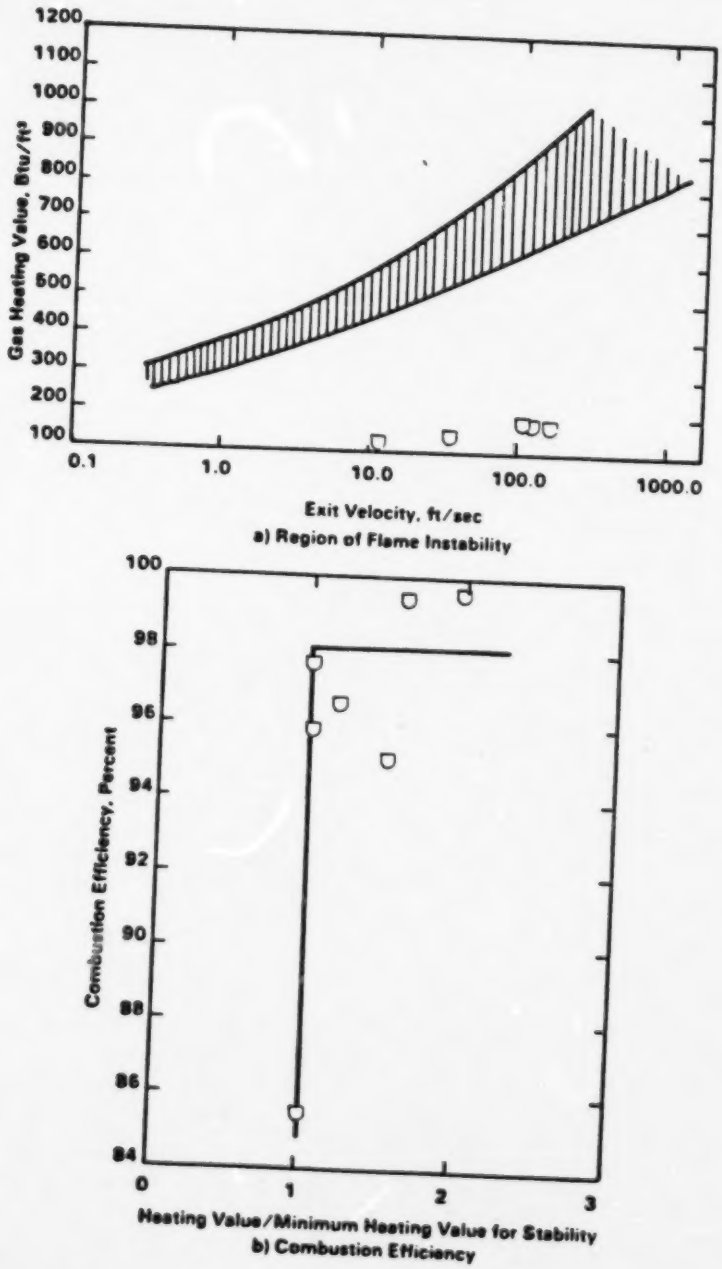
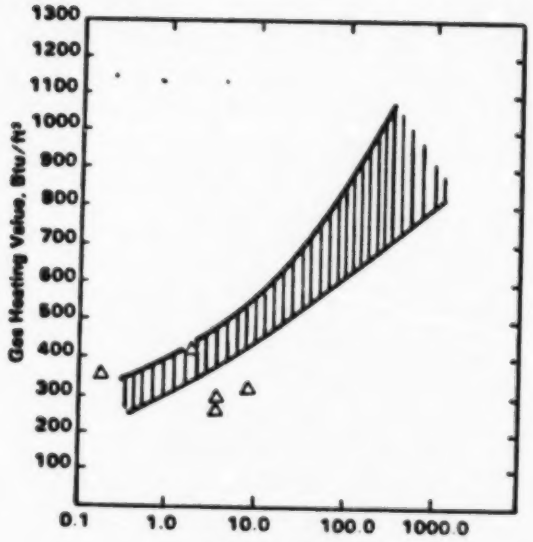
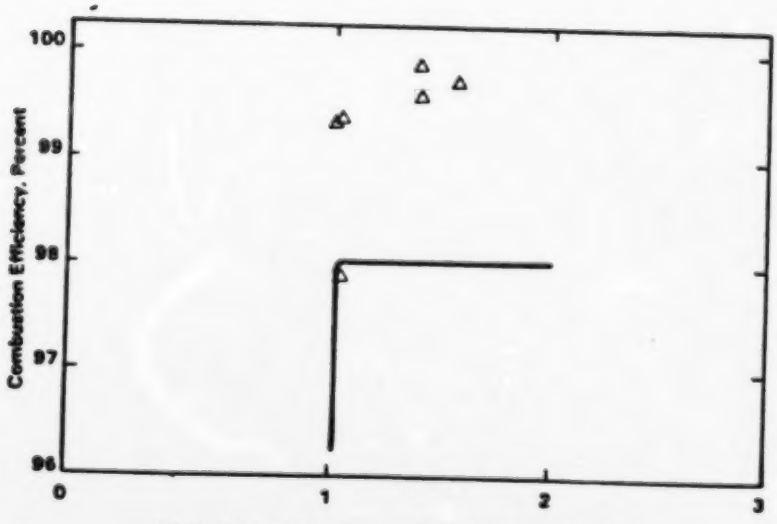


Figure 5. Region of flame stability and combustion efficiency for a commercial 1-½-in. pressure flare head F burning propane/nitrogen mixtures.

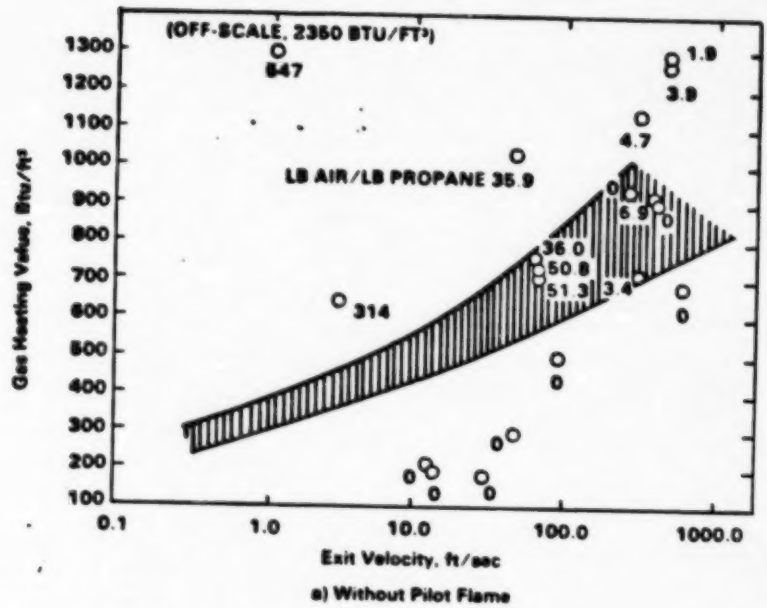


a) Region of Flame Instability

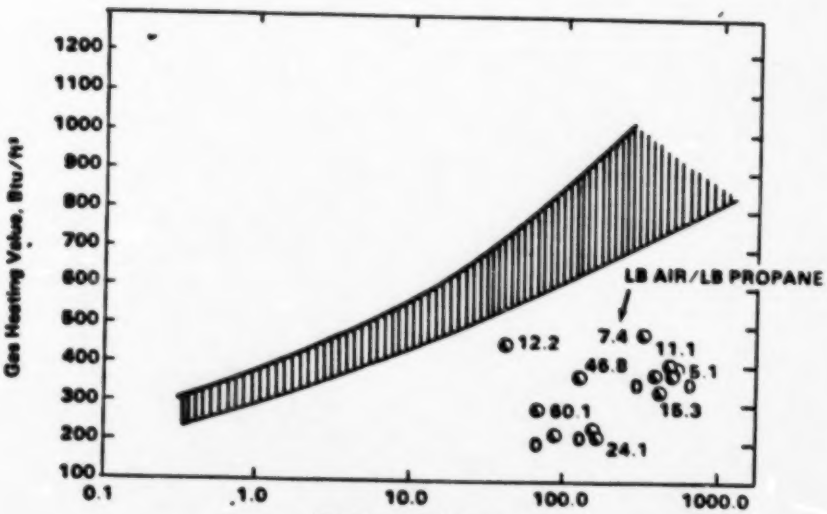


b) Combustion Efficiency

Figure 6. Region of flame stability and combustion efficiency for a commercial 12-in. Coanda steam injection flare head D burning propane/nitrogen mixtures

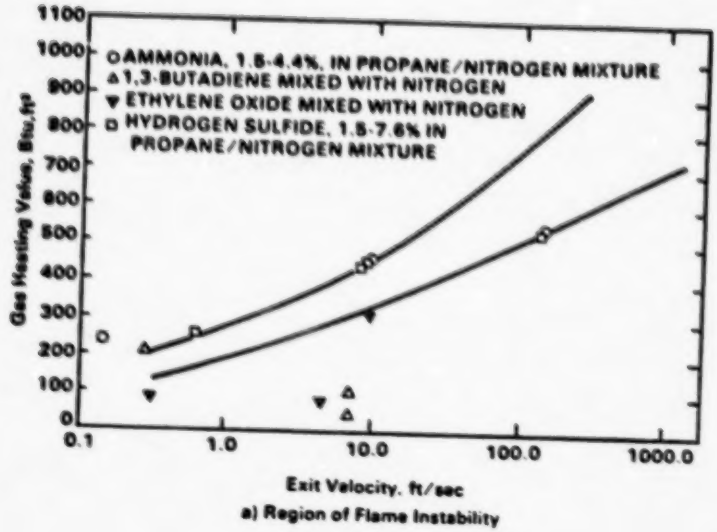


a) Without Pilot Flame

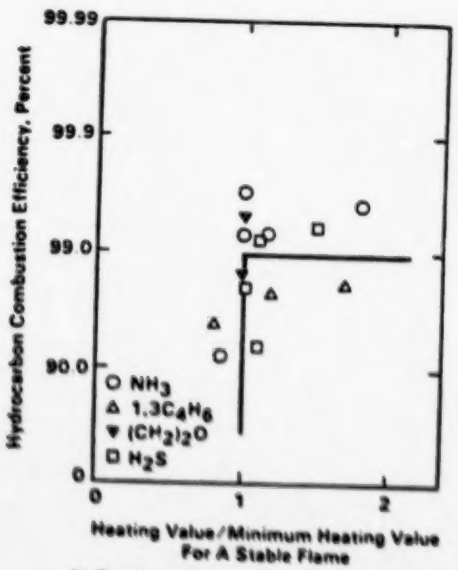


b) With Pilot Flame

Figure 7. Flame stability of air-assisted flare head G with and without pilot flame.



a) Region of Flame Instability



b) Combustion Efficiency vs. Flame Stability

Figure 8. Flame stability and combustion efficiency for 3-in. experimental flare.

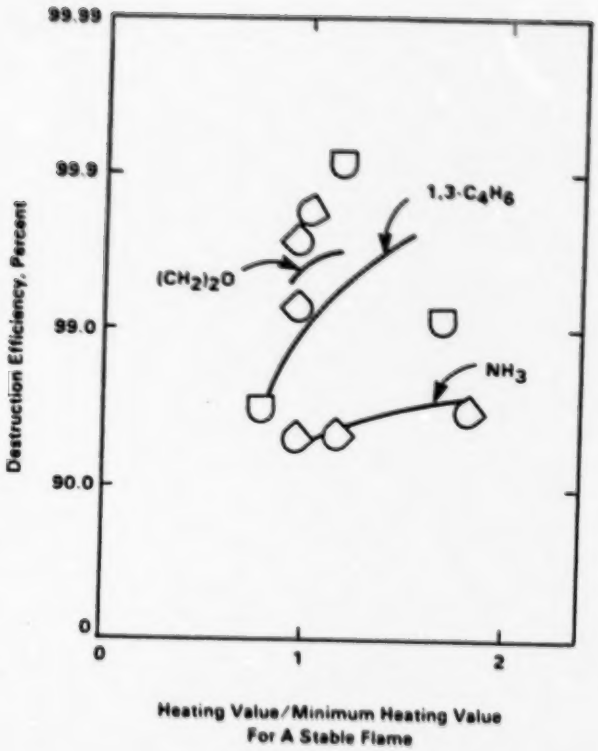


Figure 9. Destruction efficiency of gases burned on a 3-in. experimental flare head.